

HELAC(NLO) - STATUS REPORT

Costas G. Papadopoulos

NCSR “Demokritos”, Athens



Loopfest: June 22, 2010, Stony Brook, US

HELAC TEAM

Current

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Contributors

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A. Cafarella
P. Draggiotis
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HELAC TEAM



Costas G. Papadopoulos (Athens)

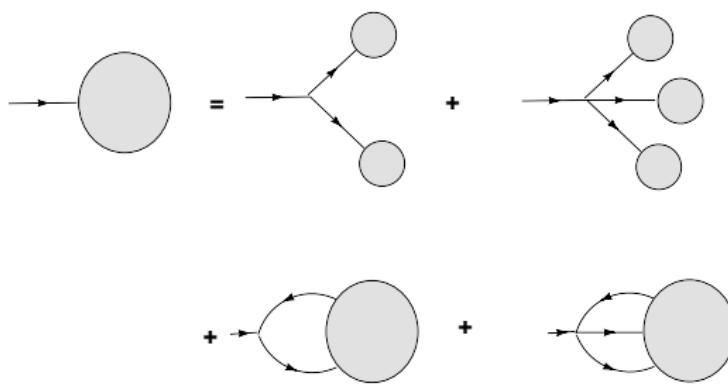
HELAC

Loopfest IX

DYSON-SCHWINGER RECURSIVE EQUATIONS

- 1999 HELAC: The first code to calculate recursively tree-order amplitudes for (practically) arbitrary number of particles

A. Kanaki and C. G. Papadopoulos, Comput. Phys. Commun. 132 (2000) 306 [arXiv:hep-ph/0002082].



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- 2000 PHEGAS: The first code to automatically produce phase-space mappings based on all FD

C. G. Papadopoulos, *Comput. Phys. Commun.* **137** (2001) 247 [[arXiv:hep-ph/0007335](https://arxiv.org/abs/hep-ph/0007335)].

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- Including all SM, in both unitary and F-gauge, masses, CKM, unstable particle widths, complex mass scheme, etc.
- For QCD color connection representation: revival of the 't Hooft ideas ('71) in the modern era.

HELAC COLOR TREATMENT

$$\mathcal{M}_{j_2, \dots, j_k}^{a_1, i_2, \dots, i_k} t_{i_1 j_1}^{a_1} \rightarrow \mathcal{M}_{j_1, j_2, \dots, j_k}^{i_1, i_2, \dots, i_k}$$

$$\mathcal{M}_{j_1, j_2, \dots, j_k}^{i_1, i_2, \dots, i_k} = \sum_{\sigma} \delta_{i_{\sigma_1}, j_1} \delta_{i_{\sigma_2}, j_2} \dots \delta_{i_{\sigma_k}, j_k} A_{\sigma}$$

gluons $\rightarrow (i, j)$, quark $\rightarrow (i, 0)$, anti-quark $\rightarrow (0, j)$, other $\rightarrow (0, 0)$

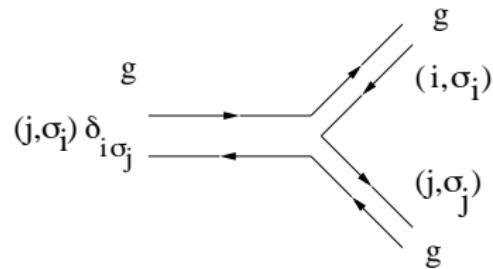
$$\sum_{\{i\}, \{j\}} |\mathcal{M}_{j_1, j_2, \dots, j_k}^{i_1, i_2, \dots, i_k}|^2$$

$$\sum_{\sigma, \sigma'} A_{\sigma}^* \mathcal{C}_{\sigma, \sigma'} A_{\sigma'}$$

$$\mathcal{C}_{\sigma, \sigma'} \equiv \sum_{\{i\}, \{j\}} \delta_{i_{\sigma_1}, j_1} \delta_{i_{\sigma_2}, j_2} \dots \delta_{i_{\sigma_k}, j_k} \delta_{i_{\sigma'_1}, j_1} \delta_{i_{\sigma'_2}, j_2} \dots \delta_{i_{\sigma'_k}, j_k} = N_c^{m(\sigma, \sigma')}$$

HELAC COLOR TREATMENT

Color-connection Feynman Rules



HELAC TREE ORDER CURRENT VERSION

- 2007 HELAC: <http://helac-phegas.web.cern.ch/helac-phegas/>

A. Cafarella, C. G. Papadopoulos and M. Worek, *Comput. Phys. Commun.* **180** (2009) 1941 [[arXiv:0710.2427 \[hep-ph\]](https://arxiv.org/abs/0710.2427)].

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- Very easy to use: just edit the `user.inp` file and then execute the command `./run.sh`

```
# Compulsory information
colpar 1      # colliding particles: 1=pp, 2=ppbar, 3=e+e-
inist 35 35    # initial state; enter 0 to sum over initial states
finst 35 35    # final state
energy 14000   # collision energy (GeV)

# For reference, here is the particle numbering:
# ve e u d vm mu c s vt ta t b a z w+ w- g h chi f+ f- jet
# 1 2 3 4 5 6 7 8 9 10 11 12 31 32 33 34 35 41 42 43 44 100
# The respective antiparticles have a minus sign (for example: positron is -2)
# A jet in the final state is denoted by the number 100

# Enter here your additional commands if you wish to alterate the default values
```

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- Generate all subprocesses for pp , $p\bar{p}$ collisions, calculate cross sections, produce Les Houches accord file
- Very easy to use: just edit the `user.inp` file and then execute the command `./run.sh`
- Including kt-reweight for jet matching
- Latest: $W + 5$ jets at LHC

- Tree-order integrated over m-body phase space + SF in D=4
- Virtual corrections integrated over m-body phase space + SF in D=4
- Real corrections subtracted integrated over (m+1)-body phase space + SF in D=4
- I- integrated over m-body phase space + SF in D=4
- KP- integrated over m-body phase space + SF integrated over SF, in D=4

THE HELAC-NLO ADVENTURE

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- 2006 OPP: The method that enables us to think seriously about NLO calculations.

Based on previous work by Bern, Dixon, Kosower, Britto, Cachazo, Feng.

Z. Bern, L. J. Dixon, D. C. Dunbar and D. A. Kosower, Nucl. Phys. B **425** (1994) 217 [[arXiv:hep-ph/9403226](#)].

R. Britto, F. Cachazo and B. Feng, Nucl. Phys. B **725** (2005) 275 [[arXiv:hep-th/0412103](#)].

Complete framework: numerical (fast) & algebraic (stable)

G. Ossola, C. G. Papadopoulos and R. Pittau, Nucl. Phys. B **763** (2007) 147 [[arXiv:hep-ph/0609007](#)].

THE HELAC-NLO ADVENTURE

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$$\begin{aligned}\int A &= \sum_{i_0 < i_1 < i_2 < i_3}^{m-1} d(i_0 i_1 i_2 i_3) D_0(i_0 i_1 i_2 i_3) \\ &+ \sum_{i_0 < i_1 < i_2}^{m-1} c(i_0 i_1 i_2) C_0(i_0 i_1 i_2) \\ &+ \sum_{i_0 < i_1}^{m-1} b(i_0 i_1) B_0(i_0 i_1) \\ &+ \sum_{i_0}^{m-1} a(i_0) A_0(i_0) \\ &+ \text{rational terms}\end{aligned}$$

Algebra & Integrals

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$$A \rightarrow \frac{N(q)}{\prod D_i}$$

$$\begin{aligned} N(q) &= \sum_{i_0 < i_1 < i_2 < i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3) \right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i \\ &+ \sum_{i_0 < i_1 < i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2) \right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\ &+ \sum_{i_0 < i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1) \right] \prod_{i \neq i_0, i_1}^{m-1} D_i \\ &+ \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0) \right] \prod_{i \neq i_0}^{m-1} D_i \end{aligned}$$

Solving for known values of the loop momentum q

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- 2007 CutTools: Reduction at the integrand level + rational terms R_1

G. Ossola, C. G. Papadopoulos and R. Pittau, JHEP **0803** (2008) 042 [[arXiv:0711.3596 \[hep-ph\]](#)].

G. Ossola, C. G. Papadopoulos and R. Pittau, JHEP **0805** (2008) 004 [[arXiv:0802.1876 \[hep-ph\]](#)].

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A. van Hameren, C. G. Papadopoulos and R. Pittau, JHEP 0909 (2009) 106 [[arXiv:0903.4665 \[hep-ph\]](https://arxiv.org/abs/0903.4665)].

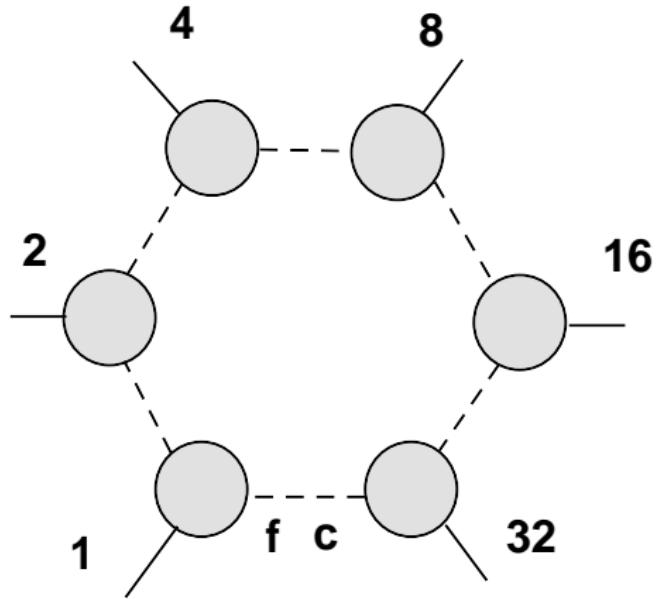
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- 2008 HELAC1L: Based on HELAC to produce virtual one-loop amplitudes
- 2009 HELAC-Dipoles: Based on HELAC to *automatically* produce Catani-Seymour dipoles, I-operator, KP-operator, arbitrary masses

M. Czakon, C. G. Papadopoulos and M. Worek, JHEP 0908 (2009) 085 [arXiv:0905.0883 [hep-ph]].

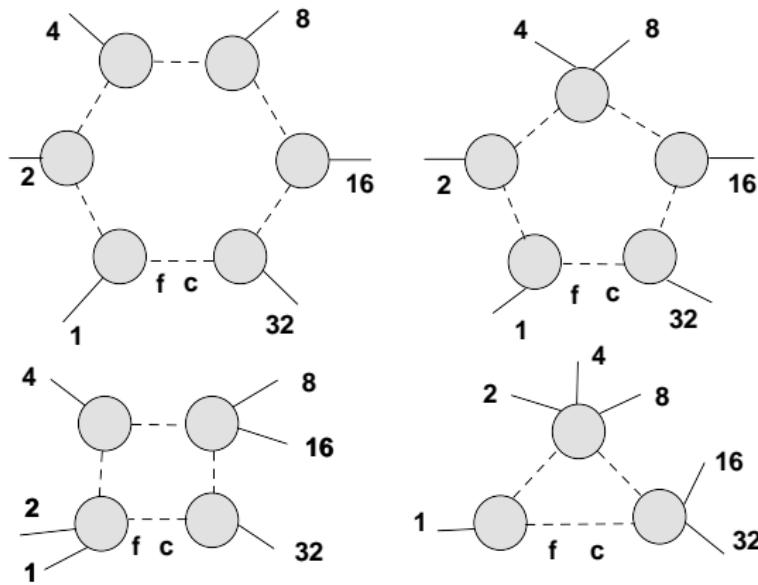
HELAC 1-LOOP

Let us consider $\alpha(1) + \beta(2) \rightarrow \gamma(4) + \delta(8) + \epsilon(16) + \zeta(32)$



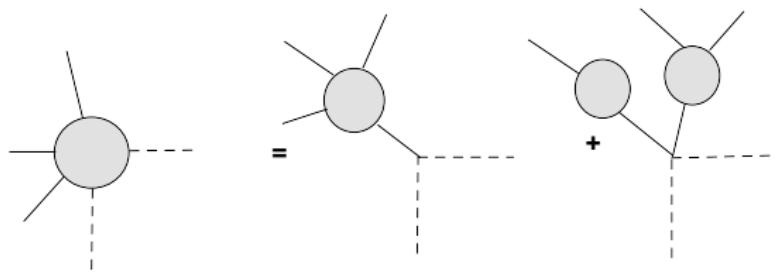
HELAC 1-LOOP

More "topologies"



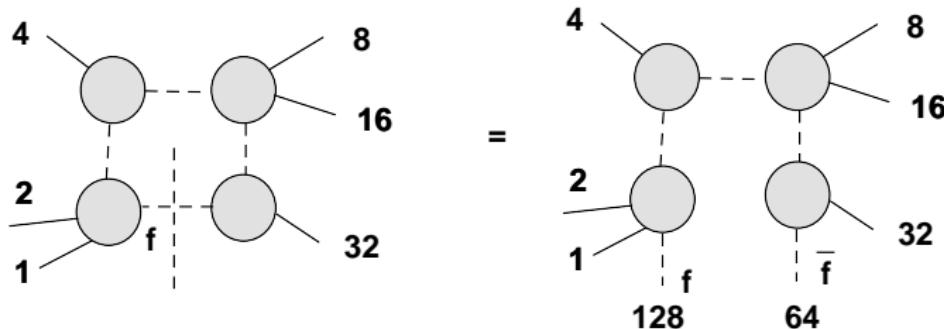
HELAC 1-LOOP

Blobs are always tree-like objects

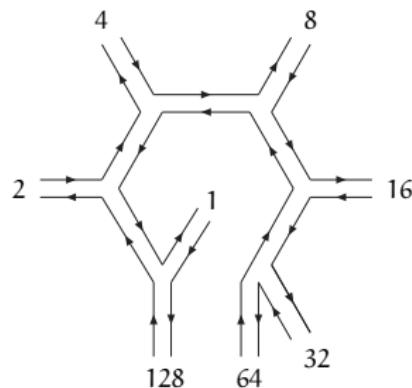
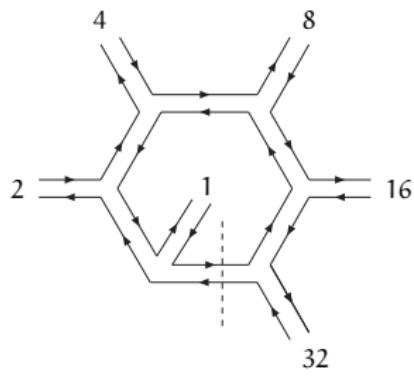
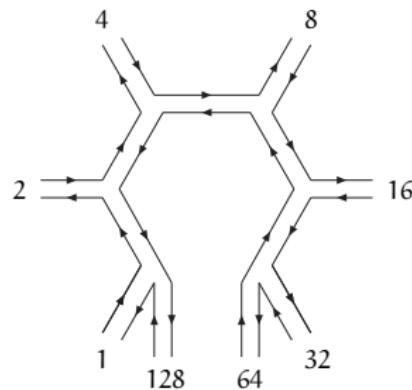
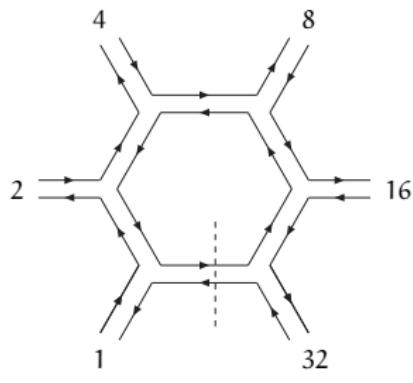


HELAC 1-LOOP

Cutting procedure to transform the problem to $n + 2$ tree-like



HELAC COLOR TREATMENT - 1 LOOP



HELAC R2 TERMS

Contribution from d -dimensional parts in numerators:

$$\overrightarrow{\mu_1,a_1} \bullet \overrightarrow{\mu_2,a_2} = \frac{ig^2 N_{col}}{48\pi^2} \delta_{a_1 a_2} \left[\frac{p^2}{2} g_{\mu_1 \mu_2} + \lambda_{HV} (g_{\mu_1 \mu_2} p^2 - p_{\mu_1} p_{\mu_2}) \right] + \frac{N_f}{N_{col}} (p^2 - 6 m_q^2) g_{\mu_1 \mu_2}$$

$$\overrightarrow{\mu_1,a_1} \bullet \overrightarrow{\mu_2,a_2} = -\frac{g^3 N_{col}}{48\pi^2} \left(\frac{7}{4} + \lambda_{HV} + 2 \frac{N_f}{N_{col}} \right) f^{a_1 a_2 a_3} V_{\mu_1 \mu_2 \mu_3}(p_1, p_2, p_3)$$

$$\begin{aligned} & \overrightarrow{\mu_1,a_1} \bullet \overrightarrow{\mu_2,a_2} = -\frac{ig^4 N_{col}}{96\pi^2} \sum_{P(234)} \left\{ \left[\frac{\delta_{a_1 a_2} \delta_{a_3 a_4} + \delta_{a_1 a_3} \delta_{a_4 a_2} + \delta_{a_1 a_4} \delta_{a_2 a_3}}{N_{col}} \right. \right. \\ & \quad + 4 \operatorname{Tr}(t^{a_1} t^{a_3} t^{a_2} t^{a_4} + t^{a_1} t^{a_4} t^{a_2} t^{a_3}) (3 + \lambda_{HV}) \\ & \quad \left. \left. - \operatorname{Tr}(\{t^{a_1} t^{a_2}\} \{t^{a_3} t^{a_4}\}) (5 + 2\lambda_{HV}) \right] g_{\mu_1 \mu_2} g_{\mu_3 \mu_4} \right. \\ & \quad \left. + 12 \frac{N_f}{N_{col}} \operatorname{Tr}(t^{a_1} t^{a_2} t^{a_3} t^{a_4}) \left(\frac{5}{3} g_{\mu_1 \mu_3} g_{\mu_2 \mu_4} - g_{\mu_1 \mu_2} g_{\mu_3 \mu_4} - g_{\mu_2 \mu_3} g_{\mu_1 \mu_4} \right) \right\} \end{aligned}$$

HELAC R2 TERMS

$\mu \xrightarrow[V]{\sim} \text{---} \bullet \begin{matrix} k \\ l \end{matrix}$

$$= -\frac{g^2}{16\pi^2} \frac{N_{col}^2 - 1}{2N_{col}} \delta_{kl} \gamma_\mu (v + a\gamma_5) (1 + \lambda_{HV})$$

$\dots \xrightarrow[S]{\sim} \bullet \begin{matrix} k \\ l \end{matrix}$

$$= -\frac{g^2}{8\pi^2} \frac{N_{col}^2 - 1}{2N_{col}} \delta_{kl} (c + d\gamma_5) (1 + \lambda_{HV})$$

$\mu \xrightarrow[V]{\sim} \text{---} \bullet \begin{matrix} p_1 & \alpha_1, a_1 \\ \text{---} & \text{---} \\ p_2 & \alpha_2, a_2 \end{matrix}$

$$= a \frac{ig^2}{12\pi^2} \delta_{a_1 a_2} \epsilon_{\mu \alpha_1 \alpha_2 \beta} (p_1 - p_2)^\beta$$

$\dots \xrightarrow[S]{\sim} \bullet \begin{matrix} \alpha_1, a_1 \\ \text{---} & \text{---} \\ \alpha_2, a_2 \end{matrix}$

$$= c \frac{g^2}{8\pi^2} \delta_{a_1 a_2} g_{\alpha_1 \alpha_2} m_q$$

$\mu_1 \xrightarrow[V_1]{\sim} \text{---} \bullet \begin{matrix} \alpha_1, a_1 \\ \text{---} & \text{---} \\ \mu_2 \xrightarrow[V_2]{\sim} \text{---} & \alpha_2, a_2 \end{matrix}$

$$= -\frac{ig^2}{24\pi^2} \delta_{a_1 a_2} (v_1 v_2 + a_1 a_2) (g_{\mu_1 \mu_2} g_{\alpha_1 \alpha_2} + g_{\mu_1 \alpha_1} g_{\mu_2 \alpha_2} + g_{\mu_1 \alpha_2} g_{\mu_2 \alpha_1})$$

HELAC 1-LOOP

INFO =====																			
INFO	COLOR	1	out	of	6	1	1	4	-4	3	8	4	4	0	0	0	0	1	2
INFO	1	12	35	7	1	1	1	4	-4	3	8	4	4	0	0	0	0	1	2
INFO	1	48	35	8	1	1	1	16	-8	5	32	8	6	0	0	0	0	1	2
INFO	2	14	-3	9	1	1	1	12	35	7	2	-3	2	0	0	0	0	1	2
INFO	2	14	-3	9	0	1	1	12	35	7	2	-3	2	0	0	0	0	2	1
INFO	2	28	-8	10	1	1	1	12	35	7	16	-8	5	0	0	0	0	1	2
INFO	2	28	-8	10	0	1	1	12	35	7	16	-8	5	0	0	0	0	2	1
INFO	3	44	8	11	1	1	1	12	35	7	32	8	6	0	0	0	0	1	2
INFO	3	44	8	11	0	1	1	12	35	7	32	8	6	0	0	0	0	2	1
INFO	2	50	-3	12	1	1	1	48	35	8	2	-3	2	0	0	0	0	1	2
INFO	2	50	-3	12	0	1	1	48	35	8	2	-3	2	0	0	0	0	2	1
INFO	2	52	-4	13	1	1	1	48	35	8	4	-4	3	0	0	0	0	1	2
INFO	2	52	-4	13	0	1	1	48	35	8	4	-4	3	0	0	0	0	2	1
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INFO	3	56	4	14	0	1	1	48	35	8	8	4	4	0	0	0	0	2	1
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INFO	1	60	35	15	4	4	52	-4	13	8	4	4	0	0	0	0	0	1	2
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INFO	2	62	-3	16	2	3	48	35	8	14	-3	9	0	0	0	0	1	1	
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INFO	2	62	-3	16	3	3	60	35	15	2	-3	2	0	0	0	0	1	1	
INFO	2	62	-3	16	0	3	60	35	15	2	-3	2	0	0	0	0	2	1	
INFO =====																			
INFO	COLOR	2	out	of	6	1	1	4	-4	3	8	4	4	0	0	0	0	1	1
INFO	1	12	35	7	1	1	1	16	-8	5	32	8	6	0	0	0	0	1	1
INFO	1	48	35	8	1	1	1	16	-8	5	32	8	6	0	0	0	0	1	1

HELAC 1-LOOP

```
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INFO COLOR 4 out of 6
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INFO NUM 1 of 143 10
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INFO 1 112 35 10 1 1 16 -8 5 96 8 9 0 0 0 0 0 1 1 1
INFO 3 120 4 11 1 1 112 35 10 8 4 4 0 0 0 0 1 1 1
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INFO 1 124 35 12 1 1 4 -4 3 120 4 11 0 0 0 0 0 1 1 1
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INFO 6 32 16 8 4 2 1 35 8 35 4 35 -3 0 0 0 0 3 1
INFOYY 1
INFO NUM 3 of 143 10
INFO 3 96 8 9 1 1 64 35 7 32 8 6 0 0 0 0 1 1 2
```

HELAC 1-LOOP

papadopo@aiolos:/tmp - Shell - Konsole																
<pre>INFO NUM 127 of 143 15 INFO 1 48 35 9 1 1 16 -8 5 32 8 6 0 0 0 0 0 1 1 1 INFO 3 112 3 10 1 1 48 35 9 64 3 7 0 0 0 0 1 1 1 INFO 3 112 3 10 0 1 48 35 9 64 3 7 0 0 0 0 0 1 1 1 INFO 1 12 35 11 1 1 4 -4 3 8 4 4 0 0 0 0 0 0 1 1 1 INFO 1 240 35 12 1 1 128 -3 8 112 3 10 0 0 0 0 0 0 -1 1 INFO 2 242 -3 13 1 1 240 35 12 2 -3 2 0 0 0 0 0 1 1 1 INFO 2 242 -3 13 0 1 240 35 12 2 -3 2 0 0 0 0 0 2 1 1 INFO 3 248 4 14 1 1 240 35 12 8 4 4 0 0 0 0 0 1 1 1 INFO 3 248 4 14 0 1 240 35 12 8 4 4 0 0 0 0 0 2 1 1 INFO 1 252 35 15 1 2 4 -4 3 248 4 14 0 0 0 0 0 0 1 1 1 INFO 4 252 35 15 2 2 12 35 11 240 35 12 0 0 0 0 0 0 1 1 1 INFO 2 254 -3 16 1 2 12 35 11 242 -3 13 0 0 0 0 0 1 1 1 INFO 2 254 -3 16 0 2 12 35 11 242 -3 13 0 0 0 0 0 2 1 1 INFO 2 254 -3 16 2 2 252 35 15 2 -3 2 0 0 0 0 0 1 1 1 INFO 2 254 -3 16 0 2 252 35 15 2 -3 2 0 0 0 0 0 2 1 1 INFO 2 48 15 3 3 0 0 0 0 0 0 0 0 0 0 0 0 0 2 5 INFOVY 5 INFO NUM 128 of 143 11 INFO 1 12 35 7 1 1 4 -4 3 8 4 4 0 0 0 0 0 1 1 1 INFO 1 48 35 8 1 1 16 -8 5 32 8 6 0 0 0 0 0 1 1 1 INFO 2 28 -8 9 1 1 12 35 7 16 -8 5 0 0 0 0 0 1 1 1 INFO 2 28 -8 9 0 1 12 35 7 16 -8 5 0 0 0 0 0 2 1 1 INFO 3 56 4 10 1 1 48 35 8 8 4 4 0 0 0 0 0 1 1 1 INFO 3 56 4 10 0 1 48 35 8 8 4 4 0 0 0 0 0 2 1 1 INFO 1 60 35 11 1 3 4 -4 3 56 4 10 0 0 0 0 0 0 1 1 1 INFO 4 60 35 11 2 3 12 35 7 48 35 8 0 0 0 0 0 0 1 1 1 INFO 1 60 35 11 3 3 28 -8 9 32 8 6 0 0 0 0 0 0 1 1 1 INFO 25 62 -3 12 1 1 60 35 11 2 -3 2 0 0 0 0 0 1 1 1 INFO 25 62 -3 12 0 1 60 35 11 2 -3 2 0 0 0 0 0 2 1 1 INFO 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 INFOVY 1 INFO NUM 129 of 143 12 INFO 23 12 35 7 1 1 4 -4 3 8 4 4 0 0 0 0 0 1 1 1 INFO 1 48 35 8 1 1 16 -8 5 32 8 6 0 0 0 0 0 1 1 1</pre>																

HELAC-1L

A. van Hameren, C. G. Papadopoulos and R. Pittau, JHEP 0909 (2009) 106 [arXiv:0903.4665 [hep-ph]].

Process		6 D_i	5 D_i	4 D_i	3 D_i	2 D_i	R_2	CT	Total
$gg \rightarrow t\bar{t}b\bar{b}$	non-planar	18	120	268	220	112	51	6	795
	planar	13	32	35	40	48	25	2	195
$gg \rightarrow t\bar{t}gg$	non-planar	168	576	480	224	56	50	14	1568
	planar	2	14	40	60	60	34	3	213

HELAC-1L

$pp \rightarrow t\bar{t}bb$			
$u\bar{u} \rightarrow t\bar{t}bb$			
	ϵ^{-2}	ϵ^{-1}	ϵ^0
HELAC-1L	-2.347908989000179E-07	-2.082520105681483E-07	3.909384299635230E-07
$I(\epsilon)$	-2.347908989000243E-07	-2.082520105665445E-07	
$gg \rightarrow t\bar{t}bb$			
HELAC-1L	-1.435108168334016E-06	-2.085070773763073E-06	3.616343483497464E-06
$I(\epsilon)$	-1.435108168334035E-06	-2.085070773651439E-06	

	p_x	p_y	p_z	E
$u(g)$	0	0	250	250
$\bar{u}(g)$	0	0	-250	250
t	12.99421901255723	-9.591511769543683	75.05543670827210	190.1845561691092
\bar{t}	53.73271578143694	-0.2854146459513714	17.68101382654795	182.9642163285034
b	-41.57664370692741	3.895531135098977	-91.94931862397770	100.9874727883170
\bar{b}	-25.15029108706678	5.981395280396083	-0.7871319108423604	25.86375471407044

HELAC-1L

$pp \rightarrow VVb\bar{b}$ and $pp \rightarrow VV + 2 \text{ jets}$			
$u\bar{u} \rightarrow W^+W^-b\bar{b}$			
	ϵ^{-2}	ϵ^{-1}	ϵ^0
HELAC-1L	-2.493916939359002E-07	-4.885901774740355E-07	1.592538533368835E-07
$I(\epsilon)$	-2.493916939359001E-07	-4.885901774752593E-07	
$gg \rightarrow W^+W^-b\bar{b}$			
HELAC-1L	-2.686310592221201E-07	-6.078682316434646E-07	-2.431624440346638E-07
$I(\epsilon)$	-2.686310592221206E-07	-6.078682340168020E-07	

	p_x	p_y	p_z	E
$u(g)$	0	0	250	250
$\bar{u}(g)$	0	0	-250	250
W^+	22.40377113462118	-16.53704884550758	129.4056091248114	154.8819879118765
W^-	92.64238702192333	-0.4920930146078141	30.48443210132545	126.4095336206695
b	-71.68369328357026	6.716416578342183	-158.5329205583824	174.1159068988160
\bar{b}	-43.36246487297426	10.31272528177322	-1.357120667754454	44.59257156863792

HELAC-1L

$pp \rightarrow V + 3 \text{ jets}$			
$u\bar{d} \rightarrow W^+ ggg$			
	ϵ^{-2}	ϵ^{-1}	ϵ^0
HELAC-1L	-1.995636628164684E-05	-5.935610843551600E-05	-5.323285370666314E-05
$I(\epsilon)$	-1.995636628164686E-05	-5.935610843566534E-05	
$u\bar{u} \rightarrow Z ggg$			
HELAC-1L	-7.148261887172997E-06	-2.142170009323704E-05	-1.906378375774021E-05
$I(\epsilon)$	-7.148261887172976E-06	-2.142170009540120E-05	

	p_x	p_y	p_z	E
u	0	0	250	250
\bar{d}	0	0	-250	250
W^+	23.90724239064912	-17.64681636854432	138.0897548661186	162.5391101447744
g	98.85942812363483	-0.5251163702879512	32.53017998659339	104.0753327455388
g	-76.49423931754684	7.167141557113385	-169.1717405928078	185.8004692730082
g	-46.27243119673712	11.00479118171890	-1.448194259904179	47.58508783667868

HELAC-1L

$pp \rightarrow t\bar{t} + 2 \text{ jets}$			
$u\bar{u} \rightarrow t\bar{t}gg$			
	ϵ^{-2}	ϵ^{-1}	ϵ^0
HELAC-1L	-6.127108113312741E-05	-1.874963444741646E-04	-3.305349683690902E-04
$I(\epsilon)$	-6.127108113312702E-05	-1.874963445081074E-04	
$gg \rightarrow t\bar{t}gg$			
HELAC-1L	-3.838786514961561E-04	-9.761168899507888E-04	-5.225385984750410E-04
$I(\epsilon)$	-3.838786514961539E-04	-9.761168898436521E-04	

	p_x	p_y	p_z	E
$u(g)$	0	0	250	250
$\bar{u}(g)$	0	0	-250	250
t	12.99421901255723	-9.591511769543683	75.05543670827210	190.1845561691092
\bar{t}	53.73271578143694	-0.2854146459513714	17.68101382654795	182.9642163285034
g	-41.57664370692741	3.895531135098977	-91.94931862397770	100.9874727883170
g	-25.15029108706678	5.981395280396083	-0.7871319108423604	25.86375471407044

HELAC-1L

$pp \rightarrow b\bar{b}b\bar{b}$			
$u\bar{u} \rightarrow b\bar{b}bb$			
	ϵ^{-2}	ϵ^{-1}	ϵ^0
HELAC-1L	-9.205269484951069E-08	-2.404679886692200E-07	-2.553568662778129E-07
$I(\epsilon)$	-9.205269484951025E-08	-2.404679886707971E-07	
$gg \rightarrow b\bar{b}b\bar{b}$			
HELAC-1L	-2.318436429821683E-05	-6.958360737366907E-05	-7.564212339279291E-05
$I(\epsilon)$	-2.318436429821662E-05	-6.958360737341511E-05	

	p_x	p_y	p_z	E
$u(g)$	0	0	250	250
$\bar{u}(g)$	0	0	-250	250
b	24.97040523056789	-18.43157602837212	144.2306511496888	147.5321146846735
\bar{b}	103.2557390255471	-0.5484684659584054	33.97680766420219	108.7035966213640
b	-79.89596300367462	7.485866671764871	-176.6948628845280	194.0630765341365
\bar{b}	-48.33018125244035	11.49417782256567	-1.512595929362970	49.70121215982584

HELAC-DIPOLES

\mathcal{E}_0 - massless emitter, \mathcal{S}_0 - massless spectator, \mathcal{E}_M - massive emitter, \mathcal{S}_M - massive spectator, \mathcal{E}_I - initial state emitter, \mathcal{E}_F - final state emitter, \mathcal{S}_I - initial state spectator, \mathcal{S}_F - final state spectator, \checkmark - check, \blacksquare - does not occur.

	$\mathcal{E}_0/\mathcal{S}_0$	$\mathcal{E}_0/\mathcal{S}_M$	$\mathcal{E}_M/\mathcal{S}_0$	$\mathcal{E}_M/\mathcal{S}_M$		$\mathcal{E}_0/\mathcal{S}_0$	$\mathcal{E}_0/\mathcal{S}_M$	$\mathcal{E}_M/\mathcal{S}_0$	$\mathcal{E}_M/\mathcal{S}_M$
$\mathcal{E}_I/\mathcal{S}_I$					$\mathcal{E}_F/\mathcal{S}_I$				
$g \rightarrow gg$	\checkmark	\blacksquare	\blacksquare	\blacksquare	$g \rightarrow gg$	\checkmark	\blacksquare	\blacksquare	\blacksquare
$g \rightarrow qq$	\checkmark	\blacksquare	\blacksquare	\blacksquare	$g \rightarrow qq$	\checkmark	\blacksquare	\checkmark	\blacksquare
$q \rightarrow qg$	\checkmark	\blacksquare	\blacksquare	\blacksquare	$q \rightarrow qg$	\checkmark	\blacksquare	\checkmark	\blacksquare
$q \rightarrow gq$	\checkmark	\blacksquare	\blacksquare	\blacksquare	$q \rightarrow gq$	\checkmark	\blacksquare	\checkmark	\blacksquare
$\mathcal{E}_I/\mathcal{S}_F$					$\mathcal{E}_F/\mathcal{S}_F$				
$g \rightarrow gg$	\checkmark	\checkmark	\blacksquare	\blacksquare	$g \rightarrow gg$	\checkmark	\checkmark	\blacksquare	\blacksquare
$g \rightarrow qq$	\checkmark	\checkmark	\blacksquare	\blacksquare	$g \rightarrow qq$	\checkmark	\checkmark	\checkmark	\checkmark
$q \rightarrow qg$	\checkmark	\checkmark	\blacksquare	\blacksquare	$q \rightarrow qg$	\checkmark	\checkmark	\checkmark	\checkmark
$q \rightarrow gq$	\checkmark	\checkmark	\blacksquare	\blacksquare	$q \rightarrow gq$	\checkmark	\checkmark	\checkmark	\checkmark

Table 1: Independent dipole splitting formulae, which need to be tested in order to ensure the correctness of the code. In the splitting description, e.g. $g \rightarrow gg$, the left hand side particle always denotes the virtual state.

HELAC-DIPOLES

PROCESS	REAL EMISSION + DIPOLES [msec]	REAL EMISSION [msec]	NR OF DIPOLES
$gg \rightarrow ggg$	3.8	1.0	27
$gg \rightarrow gggg$	8.5	2.6	56
$gg \rightarrow ggggg$	300	42	100
$u\bar{d} \rightarrow W^+ gggg$	9.3	2.4	56
$gg \rightarrow t\bar{t} b\bar{b} g$	12	2.9	55

Table 2: The CPU time needed to evaluate the real emission matrix element together with all of the dipole subtraction terms per phase-space point (this corresponds to $\alpha_{max} = 1$). All numbers have been obtained on an Intel 2.53 GHz Core 2 Duo processor with the Intel Fortran compiler using the `-fast` option.

HELAC-DIPOLES

- Arbitrary processes QCD+EW

HELAC-DIPOLES

- Arbitrary processes QCD+EW
- Massive and massless external states

HELAC-DIPOLES

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- Massive and massless external states
- Helicity (& color) sampling for partons

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HELAC-DIPOLES

- Arbitrary processes QCD+EW
- Massive and massless external states
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- Random helicities for non-partons
- Restrictions on PS α_{max}

Dipole Subtraction Configuration

only real emission: F
only last particle soft/collinear: F
only divergent dipoles: T
random polarization for non-partons: T
sign mode (0-both,1-positive,2-negative): 0
helicity sum (0-fast,1-slow,2-flat MC): 1
events with polarization sum= 100000
events for sampling optimization= 20000
event increment for sampling update= 10000
alphaMinCut= 1.00000000000000E-006
alphaMaxII= 1.00000000000000
alphaMaxIF= 1.00000000000000
alphaMaxFI= 1.00000000000000
alphaMaxFF= 1.00000000000000
kappa= 0.00000000000000E+000
jet veto included: F
pt of vetoing jet= 50.0000000000000
color sampling: F

Number of Dipoles: 55
Number of Processes: 7

HOW HELAC-NLO WORKS-VIRTUAL

Generate $w = 1$ events (Les Houches format) using HELAC at tree order.
Information included: LH + color assignment, helicity. Optimization!

HOW HELAC-NLO WORKS-VIRTUAL

Generate $w = 1$ events (Les Houches format) using HELAC at tree order.
Information included: LH + color assignment, helicity. Optimization!

```
<event>
  6 81 1.000000E+00 1.726000E+02 7.546772E-03 1.180000E-01
  21 -1 0 0 103 101 0.000000000000000E+00 0.000000000000000E+00 4.885658920243087E+02 4.885658920243087E+02 0.000000000000000E+00 0.0000000E+00 9.0000E+00
  21 -1 0 0 104 102 0.000000000000000E+00 0.000000000000000E+00 -4.885658920243087E+02 4.885658920243087E+02 0.000000000000000E+00 0.0000000E+00 9.0000E+00
  6 1 1 2 103 0 1.648551153938704E+02 -2.128833463956879E+01 1.563411288268662E+01 2.401366022681282E+02 1.726000000000000E+02 0.0000000E+00 9.0000E+00
  -6 1 1 2 0 102 -6.677109609683933E+01 6.109017946596872E+01 -3.256227583127494E+02 3.794882475549945E+02 1.726000000000000E+02 0.0000000E+00 9.0000E+00
  5 1 1 2 104 0 4.725480269309031E+00 2.281431584259000E+01 1.753945210216305E+02 1.769351891952198E+02 0.000000000000000E+00 0.0000000E+00 9.0000E+00
  -5 1 1 2 0 101 -1.02809499563402E+02 -6.261616066898994E+01 1.345941244084323E+02 1.805717450302747E+02 0.000000000000000E+00 0.0000000E+00 9.0000E+00
# 9.193930413382987E-08 4 3 4 14 13
# 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 7.869627745360847E-01 -1.175027485420859E+00 -7.869627745360847E-01
-1.175027485420859E+00
# 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 1.376454726499085E+00 -3.246111302748730E-01 -1.376454726499085E+00
-3.246111302748730E-01
# 1.863667555432868E+01 -3.562491121497572E+00 -9.077135267012881E+00 6.153194387677511E+00 -1.97062277463714E+01 -1.717507312227297E+00 -6.433090024792207E+00
-6.899515402964241E+00
# -6.580432295368123E+00 -2.321633716694498E-01 2.264652765353805E+01 1.423921666814779E+01 -2.316151832172334E+01 1.257559440674843E+01 4.439749203374159E+00
6.683084353093276E+00
# -5.059138841333641E-01 -1.133454593457765E+00 1.833599061114253E+01 -4.015116252979888E+00 1.833599061114253E+01 4.015116252979888E+00 5.059138841333641E-01
-1.133454593457765E+00
# 2.672004287479594E+00 1.755067698199695E+01 2.615285048432793E+00 -6.256029470621641E+00 -2.615285048432793E+00 -6.256029470621641E+00 2.672004287479594E+00
-1.755067698199695E+01
# pdf 3.605966723564206E-02 1.350916463377768E-01
</event>
```

HOW HELAC-NLO WORKS-VIRTUAL

Do this sum by MC (sample a configuration $\{i\} = 1, 2, 3$ $\{j\} = 1, 2, 3$)

$$\sum_{\{i\}, \{j\}} |\mathcal{M}_{j_1, j_2, \dots, j_k}^{i_1, i_2, \dots, i_k}|^2$$

Express in terms of color connections A_σ

$$\mathcal{M}_{j_1, j_2, \dots, j_k}^{i_1, i_2, \dots, i_k} = \sum_{\sigma} \delta_{i_{\sigma_1}, j_1} \delta_{i_{\sigma_2}, j_2} \dots \delta_{i_{\sigma_k}, j_k} A_{\sigma}$$

Very significant reduction in CPU-time

Process	n_{conn}	$\langle n_{conn} \rangle_{MC}$	Ratio
$gg \rightarrow b\bar{b} W^+ W^-$	6	1.74	3.5
$gg \rightarrow t\bar{t} b\bar{b}$	24	3.04	7.9
$gg \rightarrow t\bar{t} gg$	120	6.27	19.1

HOW HELAC-NLO WORKS-VIRTUAL

Generate $w = 1$ events (Les Houches format) using HELAC at tree order.
Information included: LH + color assignment, helicity. Optimization!

Calculate using HELAC-1L virtual part for each $w = 1$ event. Produce a new LH file including virtual corrections. Includes UV renormlization

HOW HELAC-NLO WORKS-VIRTUAL

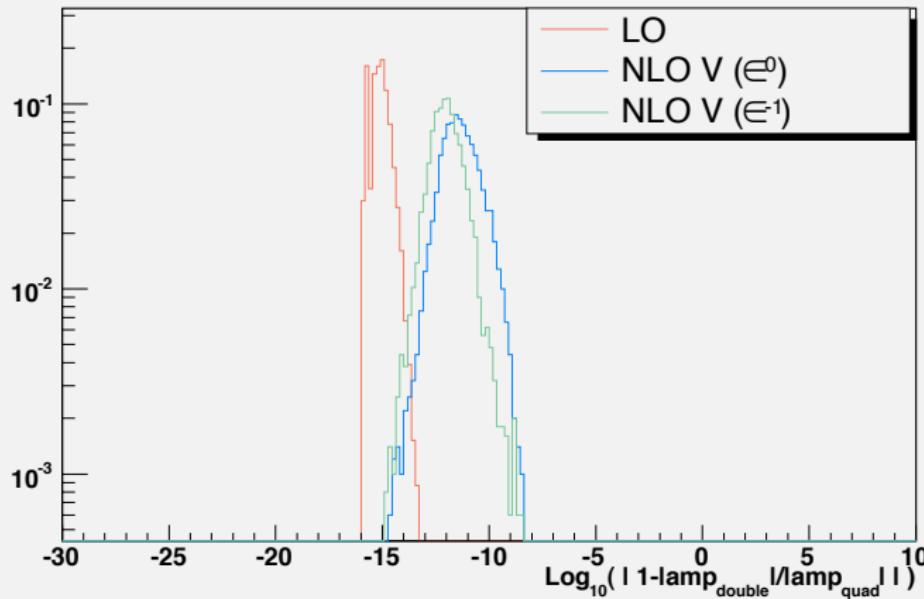
Generate $w = 1$ events (Les Houches format) using HELAC at tree order.
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Calculate using HELAC-1L virtual part for each $w = 1$ event. Produce a new LH file including virtual corrections. Includes UV renormlization

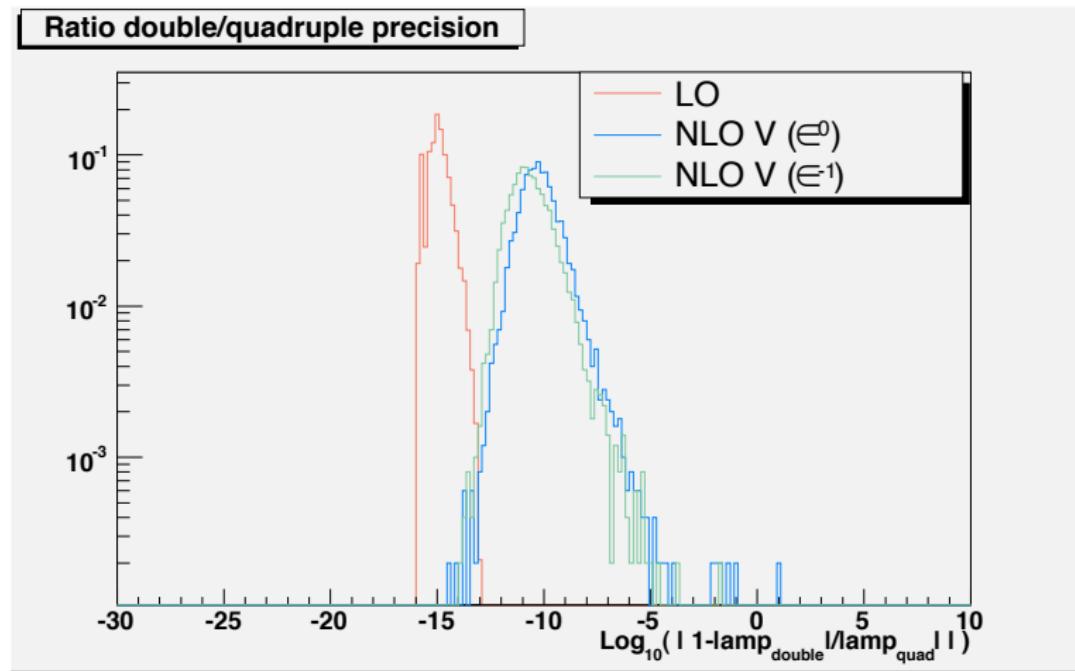
The final LH file can now be used to produce any kinematical distribution !

HOW HELAC-NLO WORKS - STABILITY

Ratio double/quadruple precision



HOW HELAC-NLO WORKS - STABILITY



HOW HELAC-NLO WORKS-REAL

HELAC-DIPOLES

Generate CS Dipoles and calculate $R - D$, jet-algorithm, histograms

HOW HELAC-NLO WORKS-REAL

HELAC-DIPOLES

Generate CS Dipoles and calculate $R - D$, jet-algorithm, histograms

Calculate I operator contributions, histograms

HOW HELAC-NLO WORKS-REAL

HELAC-DIPOLES

Generate CS Dipoles and calculate $R - D$, jet-algorithm, histograms

Calculate I operator contributions, histograms

Calculate KP operator contributions, histograms

T. Binoth, G. Ossola, C. G. Papadopoulos and R. Pittau, JHEP **0806** (2008) 082 [arXiv:0804.0350 [hep-ph]].

Process	scale μ	Born cross section [fb]	NLO cross section [fb]
ZZZ	$3M_Z$	9.7(1)	15.3(1)
WZZ	$2M_Z + M_W$	20.2(1)	40.4(2)
WWZ	$M_Z + 2M_W$	96.8(6)	181.7(8)
WWW	$3M_W$	82.5(5)	146.2(6)

Table 1: Cross section for the four processes, corresponding to the distributions in Fig 4. Different values of the factorization(renormalization) scale are used for the different processes.

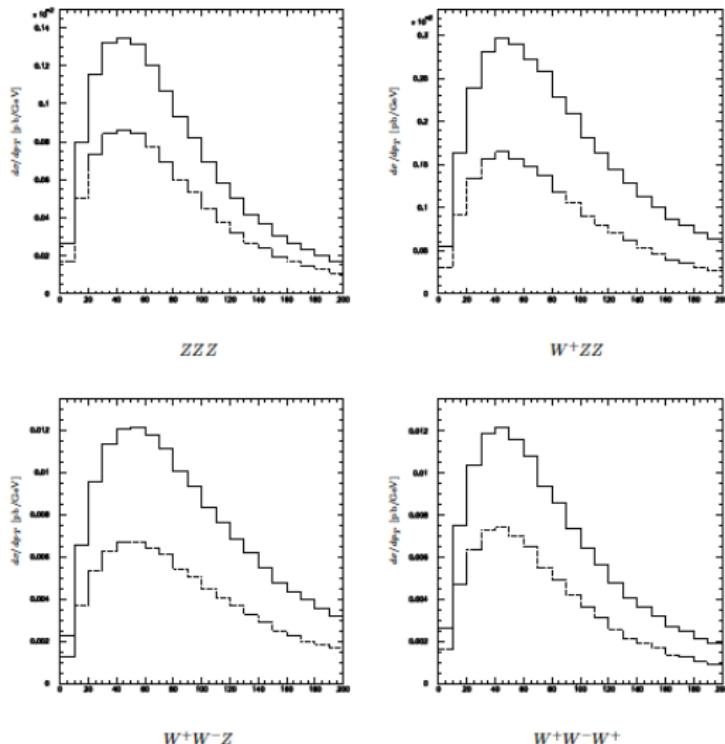


Figure 4: Transverse momentum distribution, as defined in the text, for the four processes $pp \rightarrow VVV$: NLO (solid line) compared with the LO contribution (dashed line).

$$pp \rightarrow t\bar{t}bb$$

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau and M. Worek, JHEP **0909** (2009) 109 [arXiv:0907.4723 [hep-ph]].

Setup: $\sqrt{s} = 14$ TeV, $p_{T,b} > 20$ GeV, $\Delta R > 0.8$, $|y_b| < 2.5$

$$\mu_R = \mu_F = m_t$$

Process	$\sigma_{[23, 24]}^{\text{LO}}$ [fb]	σ^{LO} [fb]	$\sigma_{[23, 24]}^{\text{NLO}}$ [fb]	$\sigma_{\alpha_{max}=1}^{\text{NLO}}$ [fb]	$\sigma_{\alpha_{max}=0.01}^{\text{NLO}}$ [fb]
$q\bar{q} \rightarrow t\bar{t}bb$	85.522(26)	85.489(46)	87.698(56)	87.545(91)	87.581(134)
$pp \rightarrow t\bar{t}bb$	1488.8(1.2)	1489.2(0.9)	2638(6)	2642(3)	2636(3)

Table 1: Cross sections for $pp \rightarrow t\bar{t}bb + X$ at the LHC at LO and NLO for the scale choice $\mu_F = \mu_R = m_t$, in comparison with the results of Refs. [23, 24]. The statistical errors are quoted in parentheses.

$$K = 1.77$$

$pp \rightarrow t\bar{t}bb$

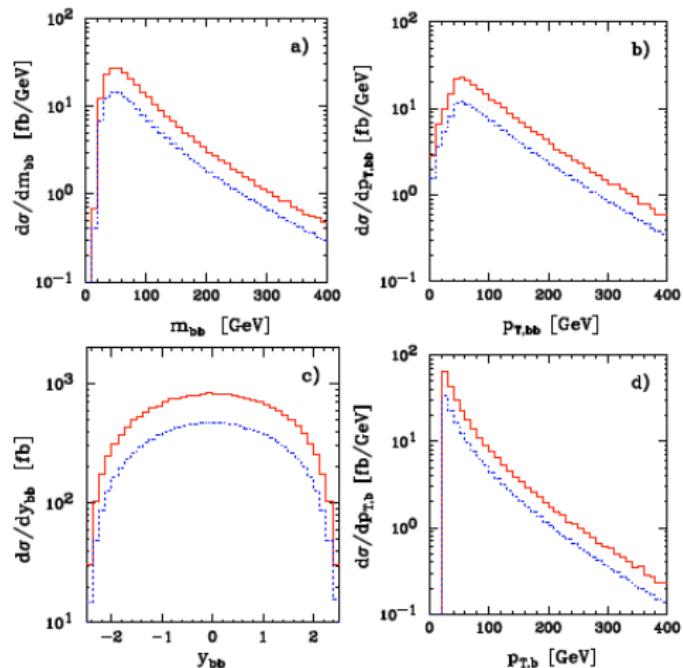


Figure 3: Distribution of the invariant mass m_{bb} of the bottom-anti-bottom pair (a), distribution in the transverse momentum $p_{T,bb}$ of the bottom-anti-bottom pair (b), distribution in the rapidity y_{bb} of the bottom-anti-bottom pair (c) and distribution in the transverse momentum $p_{T,b}$ of the bottom quark (d) for $pp \rightarrow t\bar{t}bb + X$ at the LHC at LO (blue dashed line) and NLO (red solid line). All distributions have been obtained with $\alpha_{max} = 0.01$.

$$pp \rightarrow t\bar{t}(H \rightarrow) b\bar{b}$$

"The SM and NLO multileg working group: Summary report," arXiv:1003.1241 [hep-ph].

With realistic cuts on $b\bar{b}$
 $\mu_R = \mu_F = m_t + m_H/2$

$$\sigma_{\text{LO}}^S = (150.375 \pm 0.077) \text{ fb}.$$

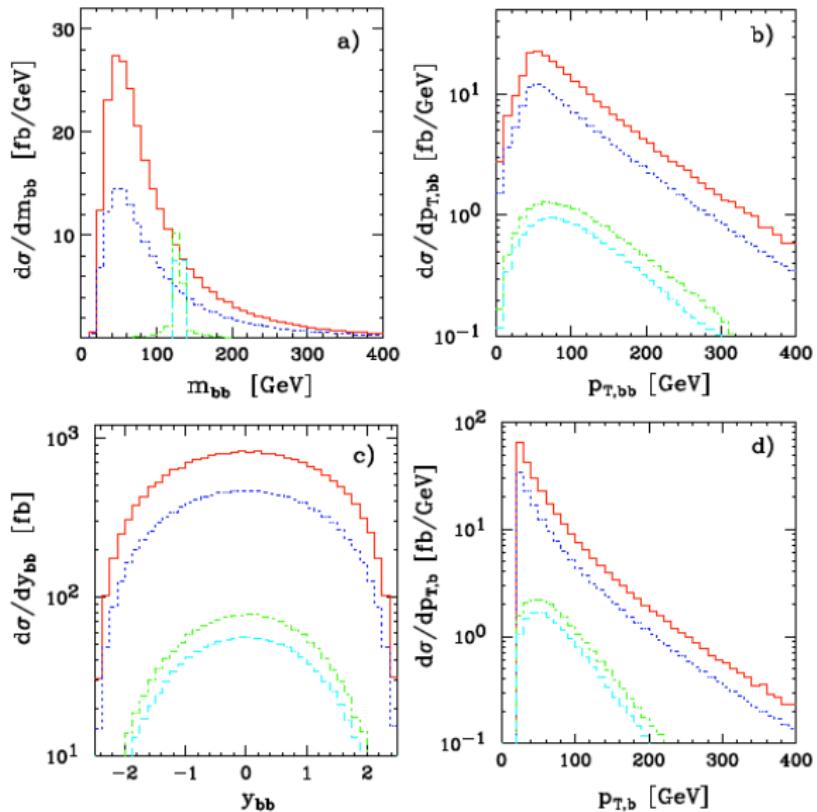
At the NLO we obtain

$$\sigma_{\text{NLO}}^S = (207.473 \pm 0.232) \text{ fb} \quad \text{for } \alpha_{\max} = 0.01,$$

$$\sigma_{\text{NLO}}^S = (207.268 \pm 0.150) \text{ fb} \quad \text{for } \alpha_{\max} = 1$$

$$K = 1.38$$

$pp \rightarrow t\bar{t}(H \rightarrow)bb$



$pp \rightarrow t\bar{t} + 2 \text{ JETS}$

G. Bevilacqua, M. Czakon, C. G. Papadopoulos and M. Worek, arXiv:1002.4009 [hep-ph].

Setup: $\sqrt{s} = 14 \text{ TeV}$, $p_{T,j} > 20 \text{ GeV}$, $\Delta R > 1$, $|y_j| < 4.5$

$$\sigma_{t\bar{t}jj}^{NLO} = (106.94 \pm 0.17) \text{ pb} \quad K = 0.89$$

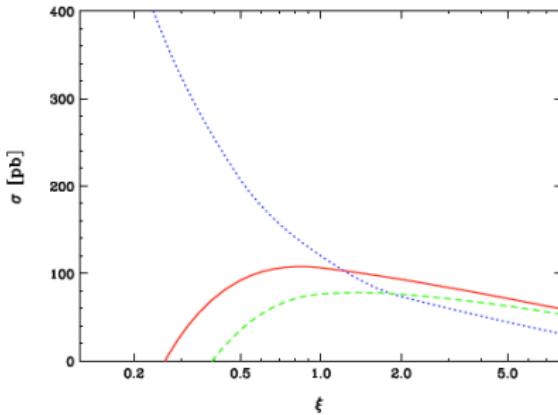
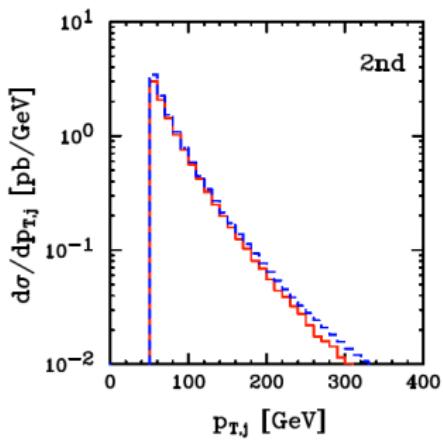
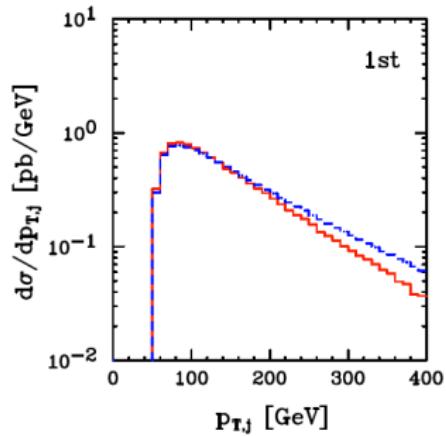


FIG. 2: Scale dependence of the total cross section for $pp \rightarrow t\bar{t}jj + X$ at the LHC with $\mu_R = \mu_F = \xi \cdot \mu_0$ where $\mu_0 = m_t$. The blue dotted curve corresponds to the LO, the red solid to the NLO result whereas the green dashed to the NLO result with a jet veto of 50 GeV.

$pp \rightarrow t\bar{t} + 2 \text{ JETS}$



Coming soon: $t\bar{t}$ +jets full analysis and $l\nu l\nu b\bar{b}$ in no-approximation

HELAC-NLO

- Complete software for NLO-QCD at LHC:
 - LO: highly automated
 - Virtual: very efficient
 - Real: KP- and I-operator contributions also very efficient,
 - Real-subtracted: quite efficient taking into account the current theoretical developments

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- Speed, stability, efficiency issues under control
 - Improvements in PS for real corrections under investigation (KALEU from A. van Hameren). Towards an order of magnitude improvement !

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- Speed, stability, efficiency issues under control
Improvements in PS for real corrections under investigation (KALEU from A. van Hameren). Towards an order of magnitude improvement !
- Provide NLO calculator for all processes $2 \rightarrow n$ with 6-7 particles attached to the loop
Providing a library of preconfigured setups for all (6-7 particles attached to the loop, up to 12 particles overall) processes of interest for LHC

BACK-UP SLIDES

For those who are interested in more details